

Present status of isobar models for elementary kaon photoproduction^{† ‡}

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Abstract: Some basic properties of isobar models are demonstrated and discussed on examples of the Saclay-Lyon and Kaon-MAID models. Predictions of these models are compared with experimental data for various processes and kinematical regions. Results of the isobar models are also compared with the Regge-isobar hybrid model, Regge-plus-resonance.

1 Introduction

Photo- and electroproduction of kaons on nucleons and nuclei plays an important role in investigating the baryon spectra and interactions in the hyperon-nucleon systems. Studying details of dynamics of the strangeness electromagnetic production we can learn more about a nature and properties of nucleon resonances which supplements information obtained in other studies in the region of nonperturbative QCD. Proper understanding of reaction mechanism is also vital for the strangeness nuclear physics. Indeed, an accurate description of the elementary production amplitude is necessary, e.g. for reliable predictions of the cross sections in electroproduction of hypernuclei as the amplitude is part of an input which determines an accuracy of predictions [1].

Description of the electroproduction process, $e + N \longrightarrow e' + K + Y$ ($N = n, p$; $K = K^+, K^0$; $Y = \Lambda, \Sigma^0, \Sigma^+, \Sigma^-$), can be formally reduced to investigation of a binary process of photoproduction by a virtual photon, $\gamma_V(q_\gamma) + N \longrightarrow K + Y$ ($q_\gamma^2 < 0$, $Q^2 = -q_\gamma^2$), since the electromagnetic coupling constant is small enough to justify the one-photon exchange approximation.

There are various ways how to describe the elementary electroproduction process. Among them the isobar model based on an effective Lagrangian description considering only hadronic degrees of freedom is suitable for more complex calculations of electroproduction of hypernuclei [1]. Another approach, suited also for description above the nucleon resonance region up to ≈ 16 GeV, is the hybrid Regge-plus-resonance model [2, 3] (RPR). This model combines the Regge model [4], appropriate to description above the resonance region ($E_\gamma > 4$ GeV), with elements of the isobar model eligible for the low-energy region. In quark models for photoproduction [5], resonances are implicitly included as excited states and therefore a number of free parameters is relatively small. Another asset of this approach is a natural description of a hadron structure which has to be modeled phenomenologically via form factors in the isobar models. However, the quark models are too complicated for their further use in the calculations of hypernucleus electroproduction.

In the effective hadrodynamical approach, various channels connected via the final-state meson-baryon interaction (rescattering processes) have to be treated simultaneously to take unitarity properly into account [6]. In the coupled-channel approach, e.g. important effects of the πN intermediate

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states can be included. Considerable simplification originates in neglecting the rescattering effects in the formalism assuming that they are included to some extent by means of effective values of the coupling constants fitted to data. This simplifying assumption was adopted in many of the isobar models, e.g. Saclay-Lyon (SL) [7], Kaon-MAID (KM) [8], and Gent-Isobar [9].

2 Isobar model

In the isobar model the amplitude is constructed by using the Feynman diagrammatic technique taking into account only contributions of the tree-level diagrams. The amplitude obtains contributions from the Born terms and s -, t -, and u -channel exchanges of the nucleon, kaon and hyperon resonances, respectively. Moreover, in some cases when gauge invariance is violated, e.g. due to hadronic form factors, a contact term is added to restore the gauge invariance. Absence of a dominant nucleon resonance in the kaon photoproduction (unlike in the π and η photoproduction) results in a large number of various combinations of the resonances with mass below 2 GeV [7] which fit the experimental data equally well. This plethora of models is limited considering constraints set by SU(3) [7, 8] and crossing symmetries [7].

A drawback of the isobar model consists in a too large contribution of the Born terms to the non-resonant part of the amplitude (background) [9]. To reduce this nonphysical contribution, either exchanges of the hyperon resonances are added [7] or the hadronic form factors (hff) in the strong vertexes are included [8]. In the Gent-Isobar model a combination of both mechanisms is used [9]. Besides a reduction of the Born terms the hff can model an internal structure of hadrons in the strong vertexes which is neglected in the effective Lagrangian. The form factors are included by a gauge-invariant technique [10] assuming dipole [8, 9], Gaussian [2] or multidipole-Gauss [3] types. These various methods of reduction of the Born terms affect strongly the dynamics of isobar model. The problem of the large Born contribution is avoided in the RPR approach.

The KM and Saclay-Lyon A (SLA) [7] models include the Born diagrams and contributions from exchanges of the $K^*(890)$ and $K_1(1270)$ resonances. The main coupling constants, $g_{KN\Lambda}$ and $g_{KN\Sigma}$, fulfill the limits of 20% broken SU(3) symmetry [7] in both models. These models differ in a choice of s - and u -channel resonances, in a treatment of the hadron structure, and in a set of experimental data to which the free parameters were adjusted. In the SLA model, one nucleon, $P_{13}(1720)$, and four hyperon resonances are included whereas in KM four nucleon, $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$, and $D_{13}(1895)$, and no hyperon resonances are assumed [8]. In the SLA model hadrons are treated as point-like objects but in KM their internal structure is modeled by means of dipole-type hffs. The SLA and KM models provide reasonable results for photon energies below 2.2 GeV.

Different dynamics of SLA and KM is shown in Figs. 1 and 2 for $p(\gamma, K^+)\Lambda$ and $n(\gamma, K^0)\Lambda$, respectively. In Fig. 1 the large forward-angle-peaked contribution from the Born terms without hff (B) is counterbalanced by the hyperon exchanges in SLA (B+h, left panel) and suppressed by the hff in KM (B+hff, right panel). In the KM model the contribution from the Born terms with hff is negligibly small which results in a dominance of contributions from the nucleon exchanges, see dash-double-dotted line in the right panel for the entire KM without $S_{11}(1650)$. A significant difference in dynamics stems from the K_1 exchange. Results without the K_1 exchange (dash-dotted lines) deviate from the full results at forward and backward angles for SLA and KM, respectively.

In $n(\gamma, K^0)\Lambda$ the Born terms reveal different angular dependence due to absence of the kaon exchange and the electric part of the proton diagram. Moreover, the anomalous magnetic moment has an opposite sign: $\mu_p = 1.79 \rightarrow \mu_n = -1.92$. This results in the backward peaked contribution

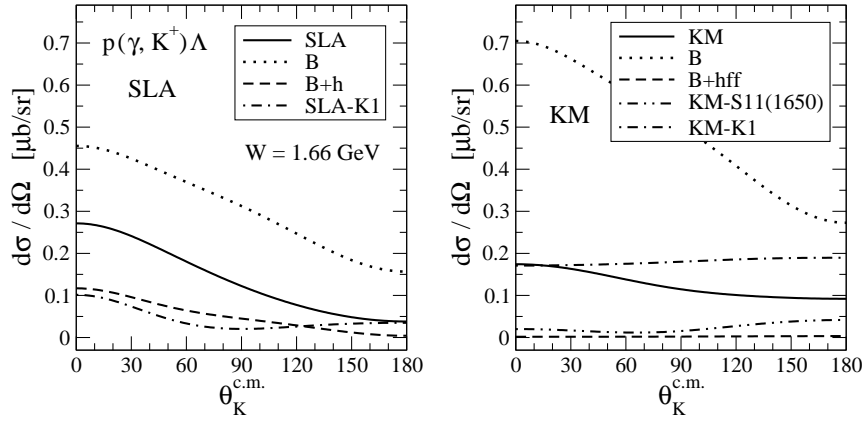


Figure 1: Dynamics of the SLA (left) and KM (right) models in $p(\gamma, K^+)\Lambda$ at $E_\gamma^{lab} = 1$ GeV. Contributions from the Born terms (B) are reduced by hyperon exchanges in SLA (B+h) and by the hff in KM (B+hff). Solid and dash-dotted lines show results of entire models and results without K_1 exchange, respectively.

of the Born terms, Fig. 2. The contribution from hyperon resonances in SLA does not change the angular dependence (left panel) whereas the hff in KM reduces significantly the Born terms as in $p(\gamma, K^+)\Lambda$ (right panel). This causes the completely different angular dependence predicted by SLA and KM for $n(\gamma, K^0)\Lambda$. A role of the K_1^0 exchange is also very different in these models. In SLA the K_1^0 exchange counterbalances the Born terms, which makes SLA very sensitive to a value of the K_1^0 coupling constant, whereas in KM the K_1^0 exchange gives a very small contribution. In Fig. 2 results of entire models without the K_1^0 exchange are shown as dash-dotted lines.

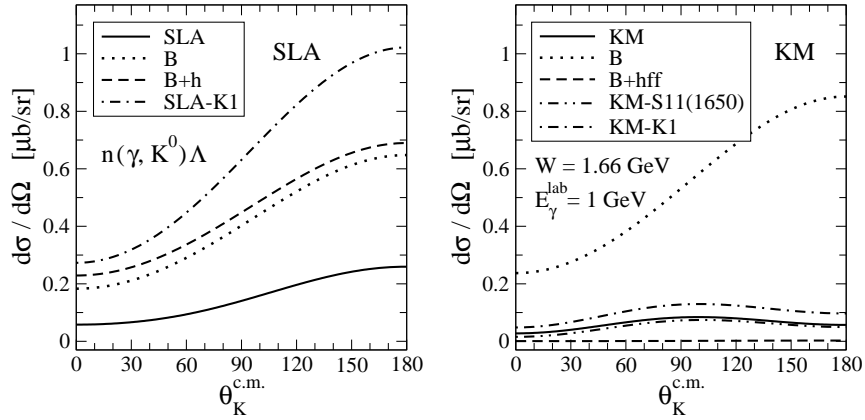


Figure 2: The same as in Fig. 1 for $n(\gamma, K^0)\Lambda$. Value of the K_1^0 coupling constant in SLA is from Ref. [11].

3 Regge-plus-resonance model

In the RPR model the non-resonant part of the amplitude is modeled by exchanges of two degenerate K and K^* trajectories. The three free parameters can be fixated from fitting to photoproduction data above the resonance region [2, 3]. The resonant part is described by exchanges of nucleon resonances like in the isobar model. A smooth transition from the resonant region into the high-energy Regge region is assured by strong hffs of Gaussian or multidipole-Gauss type [2, 3]. Important

merit of the RPR model, besides that it describes data in the energy region up to $E_\gamma^{lab} \approx 16$ GeV, is absence of large Born contributions in the non-resonant part of the amplitude. Therefore, no hffs for the background are needed which makes a difference between the RPR model and isobar model with hff, which is important for very small kaon angles, see Fig. 3.

In Fig. 3 predictions for photoproduction of K^+ are compared for isobar models with (KM, H2 [16]) and without (SLA) hff, and for three versions of the RPR model, RPR-2007 [2] and our recent versions RPR-1 and RPR-2, motivated by RPR-2011B [3] and fitted to CLAS and LEPS data below 2.5 GeV. The largest differences appear for the energy 2.2 GeV at $\theta_K^{c.m.} < 30^\circ$. The isobar models with hff (KM, H2) predict very small cross sections at zero angle and a steeply rising angular dependence, which is given by a strong suppression of the proton exchange by hff, whereas the models without hff (SLA) give a decreasing dependence and large cross sections. The RPR models can give either a plato (RPR-2007, RPR-1) or a steeply decreasing dependence (RPR-2) similarly as the SLA model.

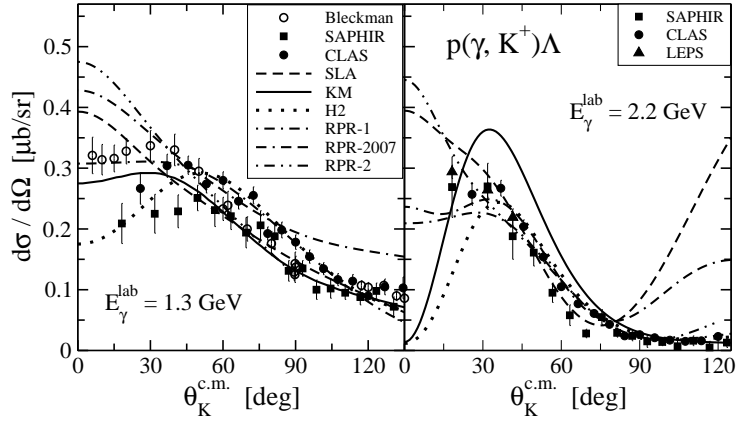


Figure 3: Comparison of isobar and RPR models with data for $p(\gamma, K^+)\Lambda$ and photon energies 1.3 and 2.2 GeV. Data are from Refs. [12](Bleckman), [13](SAPHIR), [14](CLAS), [15](LEPS).

4 Results

The differences in dynamics of the SLA and KM models in the $n(\gamma, K^0)\Lambda$ reaction, shown in Fig. 2, can be checked comparing the PWIA calculations with data for the photoproduction of K^0 on deuteron [11]. In Fig. 4 results of SLA and two versions of Kaon-MAID model, KM and KM2, for the energy-averaged and angle-integrated momentum distribution of the $K^0\Lambda$ production are shown for the energy region below 1 GeV where contributions from the Σ production are negligible. Results of SLA and KM2 were fitted to the data optimizing the K_1^0 coupling constant, see Ref. [11] for SLA, whereas KM was calculated with the original coupling constant fitted to $K^0\Sigma$ data [8]. It is apparent that SLA fits the shape of distribution very well ($\chi^2/n.d.f. = 0.64$). The Kaon-MAID model can fit only a magnitude of data points but cannot change the shape of distribution ($\chi^2/n.d.f. = 1.75$ for KM2). Angular dependence of the elementary cross sections is shown on the right panel of Fig. 4. Both fitted models, SLA and KM2, give a similar magnitude of the cross section but very different angular dependence which is given by their dynamics. The shape of angular dependence is important for a good description of the momentum distribution in the $d(\gamma, K^0)\Lambda p$ reaction, see also Ref. [11].

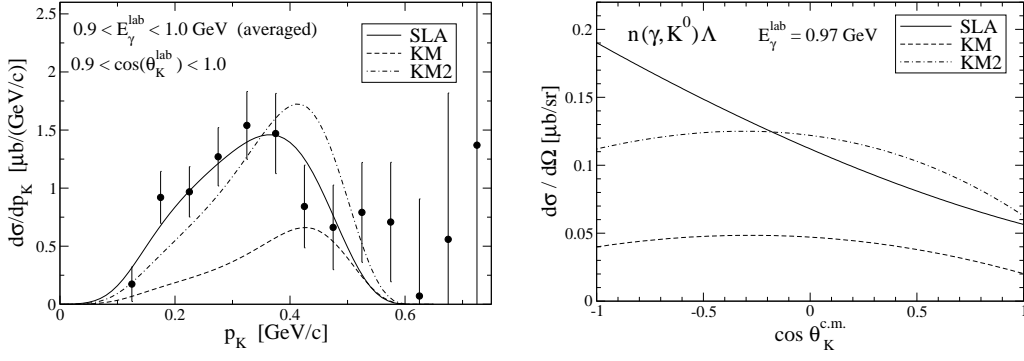


Figure 4: PWIA calculations of the energy-averaged and kaon-angle integrated momentum distribution for $d(\gamma, K^0)\Lambda p$ are compared with data [11] (left). Angular dependence of the elementary cross sections in c.m.s. at the central energy is shown for the SLA [11], KM [8] models and fitted version KM2 with $r_{K_1 K \gamma} = 0.47$.

In Fig. 5 predictions for photoproduction on nucleons (left panel) and the deuteron (right panel) with the $K^+\Lambda$ and $K^0\Lambda$ final states are shown for KM and two variants of SLA models, which differ in values of the $r_{K_1 K \gamma}$ parameter [11] shown in parenthesis in the figure. The SLA model appears to be very sensitive to the parameter $r_{K_1 K \gamma}$ which can modify both magnitude and angular dependence of the cross section. This sensitivity was also observed in Fig. 2. The SLA with $r_{K_1 K \gamma} = -1.41$ predicts the Λ -momentum-integrated cross section to be dominated by the K^0 production.

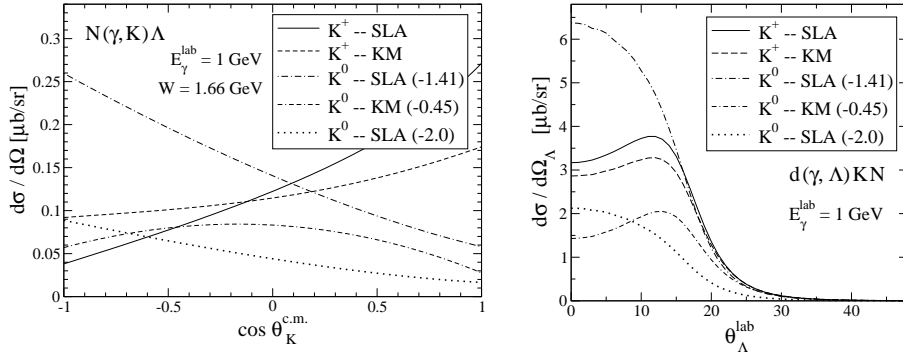


Figure 5: Cross sections for $p(\gamma, K^+)\Lambda$ and $n(\gamma, K^0)\Lambda$ predicted by the KM and two versions of SLA models (left). Values of $r_{K_1 K \gamma}$ are in parenthesis. Predictions of the Λ -momentum-integrated cross sections for $d(\gamma, \Lambda)K^+n$ and $d(\gamma, \Lambda)K^0p$ as a function of Λ laboratory angle using the elementary amplitudes (right).

In Fig. 6 results of the Regge and RPR models for the forward kaon angles are compared with data for energies above $W = 2.2$ GeV. The problem of normalization of SLAC data [19] is apparent from the energy dependence of Regge97 fitted to these data [4]. The new version, Regge2011 fitted by Gent group to CLAS data above 2.6 GeV [3], is consistent with low-energy data but underpredicts SLAC data. The SLAC data show a suppression of the cross section at zero angle and $W = 3.99$ GeV which is not observed in the low-energy region ($W = 2.24$ GeV). On the contrary, the electroproduction data point, E94-107, which is near to photoproduction, $Q^2 = 0.07$ (GeV/c)² [18], suggests rather a decreasing angular dependence. This behavior is predicted by Regge2011 and RPR-2 models. The RPR-1 and RPR-2007 [2] models suggest rather a plateau at very small angles.

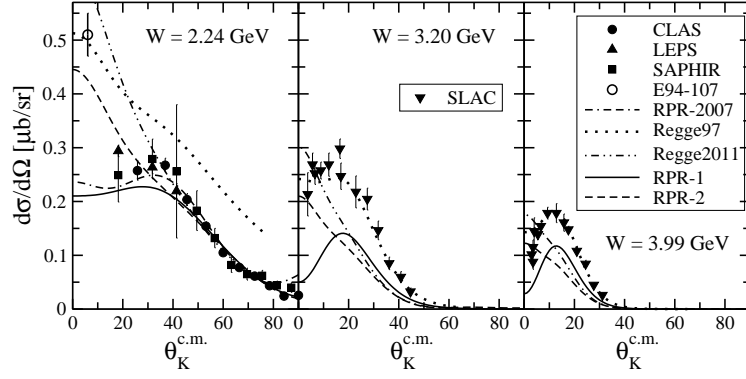


Figure 6: Results of Regge and Regge-plus-resonance models for the cross sections in $p(\gamma, K^+)\Lambda$ are compared with CLAS [14] and SLAC [17] data at forward-angle region and for energies above 2.2 GeV. The Jlab Hall A data point (E94-107) [18] is for electroproduction very near to the photoproduction point, $Q^2 = 0.07$ (GeV/c) 2 .

In electroproduction one should include in the effective Lagrangian also other possible couplings of virtual photon with baryons, e.g. “longitudinal couplings” (LC). The corresponding coupling constants can be established by fitting the Q^2 dependence of the electroproduction cross sections. This was done for the KM model using data by Niculescu et al [20]. The KM result, “KM original”, for the full unpolarized cross section with $\epsilon = 0.5$ is shown in Fig. 7 (left) in comparison with the SLA model and the re-analyzed data by Mohring et al [20]. The sharp bump for $0 < Q^2 < 0.5$ (GeV/c) 2 is modeled in KM by strong LC as it is apparent from a comparison with the result of “KM reduced” in which these couplings were removed. The SLA model which does not include LC predicts a smooth Q^2 dependence. Behavior of the cross section near the photoproduction point ($Q^2 = 0$) is shown on the right panel of Fig. 7. The MAMI data [21] at energy $W = 1.75$ GeV suggest a smooth Q^2 dependence contrary to that predicted by the original KM. The new version “KM extended” with reduced values of LC is very well consistent with the new data and the RPR-2011 [3] and SL models, see also Ref. [21].

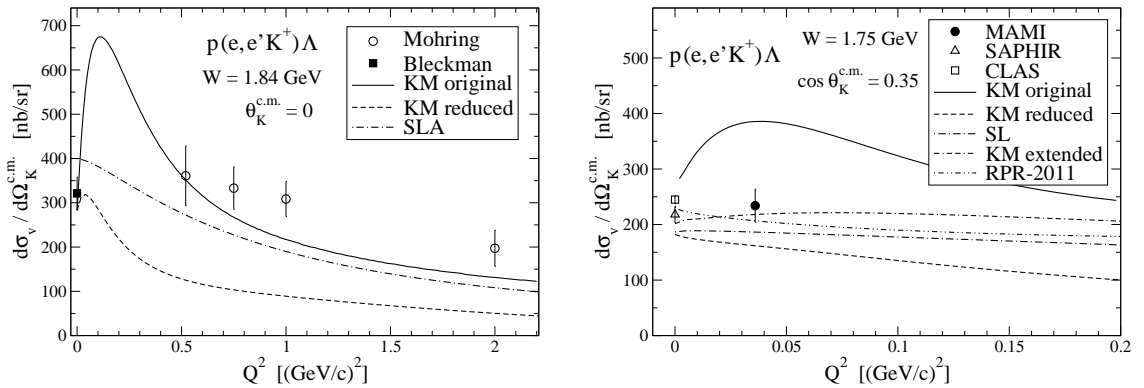


Figure 7: Predictions of the isobar models for the electroproduction cross section are compared with data to show behavior near the photoproduction point ($Q^2=0$).

5 Summary

Data on the K^0 photoproduction on deuteron can be used for testing the isobar models. More data for very small kaon angles and wide energy range are needed to shed light on the angular and energy dependence of the cross section and dynamics of isobar models in this kinematical region. Recent data for very small Q^2 suggest that longitudinal couplings are not too much significant in the isobar models.

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